

Fig. 3. Gravity profiles taken across the Chicxulub basin at 10° intervals of azimuth. D_t and D_a refer to the transient crater diameter and final or apparent crater diameter resulting from this analysis. Profiles are offset vertically by 10 mgal; the annotated vertical axis shows the 0 mgal value for the designated profiles, beginning from the bottom with north to south. Dashed profile is due east to west. The value of the center point of each gravity profile is 10.4 mgal.

most similar to Earth is Venus. Evaluation of over 1000 impact craters detected by the Magellan spacecraft reveal that double-ring, or peak-ring basins are constrained to diameters between 40 km and 110 km [16]. All larger craters are multiring basins, i.e., basins characterized by three or more concentric rings. This, coupled with the evidence above, suggests that the previous model of Chicxulub as a ~180-km-diameter peak-ring basin is incorrect.

Consequently, we believe the interpretation most consistent with all available information is that the Chicxulub structure is a ~300-km-diameter multiring basin (Fig. 4) similar to the largest impact landforms observed on the Moon, Mercury, and Venus [14]. Such events are extremely rare; there is only one other impact basin of comparable size produced in the inner solar system within the last billion or so years: the 280-km Mead Basin on Venus.

Chicxulub Multiring Basin and the KT Boundary: Melt rocks within the Chicxulub Crater have experienced varying levels of hydrothermal alteration and albitization [17]; however, ^{40}Ar - ^{39}Ar determinations on relatively pristine melt rock samples from the center of the basin indicate a crystallization age at or very near the KT boundary [6,10]. Evaluation of the magnetization of these and other samples show that they cooled during an episode of reversed geomagnetic polarity, consistent with a KT boundary age [6,18]. Analysis of the Rb-Sr, O, and Nd-Sm isotopic systems confirm a chemical link between the Chicxulub melt rocks and the impact glasses contained in the KT boundary deposits at Beloc, Haiti [11]. Unmelted breccia clasts, representing the silicate base-

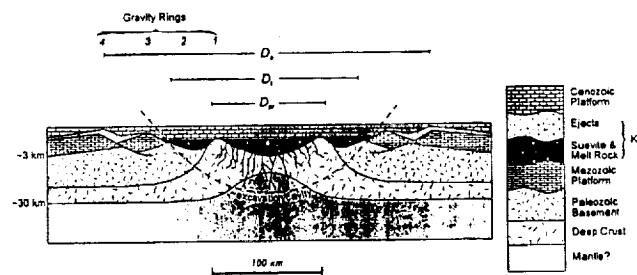


Fig. 4. A schematic model of the Chicxulub impact basin that we derive from this analysis. This simplified cross section shows the general configuration of the crater but does not consider erosion; erosion at the time of impact could rearrange the upper crater units significantly and reduce crater topography. Faults and unit boundaries are simplified.

ment impacted by the Chicxulub basin forming event, are medium- to high-grade continental crust similar to the lithic clasts observed within KT boundary sediments from around the world [6,19].

Krogh et al. [8] recently determined that U-Pb ages of zircon xenocrysts from a Chicxulub breccia sample are ~545 Ma, with a small percentage showing a 418-Ma age. These 545-Ma-old zircons match the crystallization age of those within the upper member (magic layer, fireball layer, etc.) of the KT doublet in the Raton Basin of New Mexico. This provides compelling evidence that the Chicxulub impact event is responsible for both the shocked minerals observed in the upper member of the KT boundary sequence and the glass-rich lower member. Consequently, all evidence to date points to a singular, extremely energetic, and deadly impact event at the KT boundary.

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WERE ALL EXTINCTION EVENTS CAUSED BY IMPACTS? P.M. Sheehan and P.J. Coorough, Department of Geology, Milwaukee Public Museum, 800 W. Wells Street, Milwaukee WI 53233, USA.

Extraterrestrial impacts are firmly implicated in several of the five major Phanerozoic extinction events. A critical issue now is whether extraterrestrial events have been the only mechanism that produced physical changes of sufficient magnitude to cause major extinction events [1,2].

While we believe the evidence is overwhelming that the KT extinction event was caused by an impact [3,4], we also find that an event of similar or larger size [5] near the end of the Ordovician is best explained by terrestrial causes [6–9].

The Ordovician extinction event (End-O extinction event) occurred near the end of the Ordovician, but the interval of extinction was completed prior to the newly established Ordovician-Silurian boundary [6]. In spite of extensive field studies, a convincing signature of an associated impact has not been found [10–13]. However, a prominent glaciation does coincide with the End-O extinction event.

Late Ordovician Glaciation and Extinction: During the Late Ordovician sea level was high, and broad epicontinental seas covered most continental plates. The Baltic, Laurentian, and Siberian plates were isolated and inhabited by zoogeographically discrete faunas. Extensive glacial features in North Africa document a Late Ordovician glaciation that lasted for 2–3 m.y. [14,6,8]. Sea level declined as water was transferred to the ice caps, and the epicontinental seas were drained. River drainage systems were incised into the carbonate platforms. Albedo changes caused by progressive exposure of the sea floor may have intensified the glaciation [15]. Drop-stones from icebergs were present in high-latitude oceans [16]. The glaciation ended abruptly, as evidenced by rapid eustatic rise in global sea level. Oxygen and C isotopic studies are consistent with ocean chemistry changes expected during the glaciation [17–19].

The End-O extinction event tracked the glacial epoch. Epicontinental sea faunas were decimated by the regression that marked the beginning of the glaciation [20,8]. Around the margins of many continents a new fauna called the *Hirnantia* fauna appeared and replaced older stocks. Many elements of the *Hirnantia* fauna originated in high latitudes. The appearance of the *Hirnantia* fauna commonly corresponds with a change from warm-water, carbonate rocks to cool-water, siliceous rocks.

As the glaciation intensified, planktonic groups, such as graptolites, progressively became restricted to the tropics [20]. The glaciation increased oceanic circulation, which in turn oxygenated previously anoxic areas of the oceans, reducing the habitat of some planktic organisms including graptolites [21], but providing new habitat for other benthic organisms [8]. A pulse of extinction during an interglacial event may have eliminated some benthic animals [6]. At the end of the glacial epoch climatic warming, sea level rise, and the return of anoxic waters dealt the final blow to the ecosystem [6].

Ecologic patterns changed significantly during the extinction interval. Long-standing communities of animals were decimated. New communities evolved during the glacial interval, but these communities were eliminated when the glaciation ended. A third set of communities was established in the Silurian, and recovery of the ecosystem required several million years [22].

Zoogeographic patterns were also disrupted. In the Late Ordovician highly endemic faunas formed distinct zoogeographic provinces in the epicontinental seas on each of the isolated continental plates. These provinces were eliminated by the extinction and survivors were dominated by animals with wide geographic distribution. The postextinction interval was characterized by the some of the most cosmopolitan faunas in the geologic record [7]. Tens of millions of years of evolution in isolated seaways were required before prior levels of provincialism were attained.

Study of a Non-Impact-Related Extinction Event: Study of the End-O extinction event is more difficult than studying the KT

event because an impact clay is missing, so there is no worldwide event horizon to which phenomena can be tied. Correlation in the Ordovician relies primarily on fossil data and the extinction reduced the number of species that were available for correlation. Graptolites and conodonts, the two groups most useful for correlation, were especially hard hit. Postextinction species tended to have exceptionally long geologic ranges, making correlation following the extinction difficult. Some events, such as the appearance of the *Hirnantia* fauna in two different areas, may be mistakenly taken to be synchronous. The *Hirnantia* fauna was a cold-water fauna that apparently moved toward the tropics as the glaciation intensified. Thus, the first appearance of the *Hirnantia* fauna probably happened at different times in different places. Eustatic sea level rise and fall may prove to be the most accurate method of correlation during this interval.

Comparison of Impact and Nonimpact Extinction Events: Even though the End-O extinction event had a terrestrial cause, it was still catastrophic. The physical perturbation of the environment was beyond the ability of the ecosystem to adapt through normal evolutionary processes.

The primary difference between the KT and End-O extinction events was the duration of the events. The KT event was instantaneous on a geologic timescale, and postimpact perturbation of the physical environment lasted less than a million years. The End-O event had an extinction interval of 2–3 m.y. with several pulses as the ice caps advanced and retreated.

In spite of these differences, the effect on the Cretaceous and Ordovician biotas was quite similar. An impact and a glaciation are capable of producing similar levels of extinction at family and generic levels [5,22]. In both cases long intervals of ecologic stability were disrupted, and new ecologic communities and provinces were established [23].

There is currently a paradigm shift underway in paleontology from one that views evolution as pervasively gradual to a paradigm of gradual evolution punctuated by occasional catastrophic events that are accompanied by restructuring of the entire ecologic landscape. Determining whether or not these catastrophic events include both terrestrial and extraterrestrial events is imperative.

If some extinction events are not caused by impacts, there is a wild card in the current search for periodicity of extinction events. If one of the five major Phanerozoic extinction events had a terrestrial cause, many smaller events also may have had terrestrial causes. The history of life might include a group of extinction events caused by periodic impacts and another group of extinction events with non-periodic, terrestrial causes.

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OZONE CONTROL OF BIOLOGICAL ACTIVITY DURING EARTH'S HISTORY, INCLUDING THE KT CATASTROPHE. W. R. Sheldon, University of Houston, Houston TX 77204-5506, USA.

There have been brief periods since the beginning of the Cambrian some 600 m.y. ago when mass extinctions destroyed a significant fraction of living species. The most widely studied of these events is the catastrophe at the KT boundary that ended the long dominance of the dinosaurs. In addition to mass extinctions there is another profound discontinuity in the history of Earth's biota, the explosion of life at the end of the Precambrian era, an episode that is not explained well at all. For some 3 b.y. before the Cambrian, life had been present on Earth, but maintained a low level of activity, an aspect of the biota that is puzzling, especially during the last two-thirds of that period. During the last 2 b.y. before the Cambrian, conditions at the Earth's surface were suitable for a burgeoning of the biota, according to most criteria: The oceans neither boiled nor were frozen solid during this time, and the atmosphere contained sufficient O for the development of animals. The purpose of this paper is to suggest that mass extinctions and the lackluster behavior of the Precambrian biota share a common cause: an inadequate amount of ozone in the atmosphere.

Calculations of atmospheric ozone O₃ have been made with the concentration of O₂ in the atmosphere as a variable parameter [1,2], but with the solar spectrum at the top of the atmosphere assumed to be that observed at present. On the basis of these calculations it is of interest to note that the present ozone atmosphere is only some 30% above the critical value of 7×10^{18} O₃ cm⁻², a level that provides a "full screen" for the biota; however, an O₂ concentration only 10% of the present atmospheric level (PAL) creates an ozone atmosphere only 20% below the critical value. Consequently it has been assumed that when the O₂ concentration reached the neighborhood of 10⁻¹ PAL, the biota found an environment on the Earth's surface relatively free of degradation from solar ultraviolet (UV) radiation. Here that concept is questioned and a scenario is described in which a robust O₂ atmosphere could be present, but an O₃ atmosphere anywhere near the critical value would not be formed.

Present concern for the Earth's ozone layer is focused on chemical processes in the atmosphere that destroy O₃; the ozone production rate is constant and not considered to be a potential problem. In

the geologic past such was certainly not the case and the main point of this paper is that during the Earth's history the O₃ production rate has been the controlling factor for the biota. Specifically, it is suggested that cometary activity during the Precambrian and comet showers during mass extinction events provided a supply of volatile material to the inner solar system that selectively absorbed UV photons capable of photolyzing the O₂ molecule (and thus precluded O₃ production); at the same time the solar flux at near-UV wavelengths arrived at Earth unattenuated, resulting in an extremely harsh environment for the biota at the Earth's surface and at ocean depths down to several tens of meters.

The comets under consideration consisted of volatile material that accumulated in the region of the nebular disk beyond Jupiter's orbit. Then gravitational perturbations by the four giant planets redistributed a portion of these cometary bodies to form the Oort comet cloud at the outer boundary of the solar system [3]. At the same time a much larger number of these bodies were expelled from the solar system, or were disrupted and vaporized by passing in the vicinity of the Sun [4,5].

In order to estimate the amount of cometary volatile material that is required to have a critical effect on O₃ production in the atmosphere it is assumed that the rate of O photolysis ($O_2 + h\nu \rightarrow O + O$) required for O₃ production is proportional to the flux of photons in the extreme UV that drive the reaction; further it is assumed that a reduction of the O₃ production rate of $\frac{1}{2}$ of its present value would result in an environment sufficiently harsh at the Earth's surface to account for the Precambrian biota or mass extinctions. In the present atmosphere the flux of 200-nm photons is reduced to $\frac{1}{2}$ of its value at the top of the atmosphere by $\sim 10^{23}$ O₂ molecules per cm². However, the cometary volatile material would consist of water (H₂O) and ammonia (NH₃), molecules with UV absorption cross sections greater than that of O₂ by factors of 10 and 10⁶, respectively [2]. Thus an average concentration of $\sim 7 \times 10^8$ cm⁻³ of H₂O, or $\sim 7 \times 10^3$ cm⁻³ of NH₃, would be required along the path connecting the Earth and the Sun. If the cometary material is constrained to a disk 0.1 AU thick the total amount of H₂O would be 2×10^{25} g, or 10^{20} g of NH₃. Comparing the collision cross sections of the Earth and the disk (a factor of 5×10^7), it is concluded that during the same period of time cometary transport would deposit 4×10^{17} g H₂O on Earth, or 2×10^{12} g NH₃. Assuming a residence time of one year for vaporized material in the disk (corresponding to an average velocity of 50 km s⁻¹ for the outward transport of the vapor), during the 3×10^9 years of cometary activity in the Precambrian 1.2×10^{27} g H₂O, or 6×10^{21} g NH₃, would have been deposited on Earth.

It is appropriate to consider two aspects of this proposed scenario for the effect of comets on the history of Earth's biota: whether it is possible and what, if any, further conclusions would result. The most direct quantitative comparison involves the total amounts of H₂O or NH₃ predicted to have been deposited on Earth by cometary activity [6,7]. The amount of H₂O alone that would be required exceeds the amount on Earth by more than 2 orders of magnitude, but the amount of NH₃ required is about equal to the mass of Earth's atmosphere. Thus the proposed scenario seems to meet the zeroth order test, especially where NH₃ is concerned. However, it should be noted that the required amount of volatile material could be an overestimate, since the absence of an O₃ atmosphere for perhaps only 1% of the time during the Precambrian could suffice to suppress the development of the biota on the Earth's surface. Another consideration is the fact that solar luminosity was less during the